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Optimal Placement of Distributed Energy Resources to Reduce Losses, Improve Voltage Profile, and Convert it into a Self-healing Smart Grid

Ali Kazemi, Ali Morsagh Dezfuli

Highlight

- Achieving a self-healing network with high reliability and minimal losses
- Optimal placement of DGs in the network using the particle swarm algorithm
- Enhancing the voltage profile and system reliability
- Detecting and rectifying disruptions with minimal human intervention

Graphical Abstract

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Optimal Placement of Distributed Energy Resources to Reduce Losses, Improve Voltage Profile, and Convert it into a Self-healing Smart Grid

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ABSTRACT

This study focuses on achieving a self-healing network with high reliability and minimal losses by discussing the optimal placement of distributed generation (DG) sources in the network using the particle swarm algorithm (PSO). Optimal placement not only reduces losses but also enhances the voltage profile and enhances system reliability. Consequently, the paper explores the concept of a self-healing smart grid. Smart grids possess a crucial attribute known as self-healing, designed to enhance the system's dependability. The self-healing power grid can detect and rectify disruptions within its infrastructure with minimal or even absent human intervention. This study examines a standard IEEE 69-bus network and presents results demonstrating the network's safety, the prevention of blackouts, the reduction of losses, and the substantial enhancement of the voltage profile.

1. Introduction

The growing demand for clean and affordable energy, along with advancements in renewable resources technology, has led to a rising trend in distributed generation. Conversely, the utilization of distributed generation (DGs) units in energy distribution networks can yield several outcomes, including loss reduction, enhanced dependability, improved voltage profile, and enhanced power quality in electrical distribution networks. The strategic placement of DGs inside a distribution network is crucial for attaining these objectives. Within distribution networks, the voltage profile is inadequate in terms of voltage magnitude, and power loss is unavoidable. Therefore, the investigation of the impact of DGs is necessary to enhance the voltage profile magnitude, minimize losses, and improve reliability. Additionally, determining the optimal location of these sources is crucial in achieving these objectives. Parametric relations and cost functions are utilized in [1] to determine the optimal placement of DGs in a network with unbalanced loads. Additionally, the group search optimizer (GSO) is employed as a novel method for resolving unbalanced power flow. This is one of the recently developed algorithms in the field of neural networks. The paper [2] presents a method for determining the best location for DGs by minimizing the overall energy loss. This method uses nonlinear programming and optimal power flow (OPF) techniques, taking into account operational

constraints and uncertainties in load and power generation resources in the IEEE 33-bus test system. The unit commitment (UC) problem is addressed in [3] using a novel evolutionary approach. The conventional objective function of the UC problem involves taking into account the pertinent parameters of the wind farm and aiming to enhance the quality of life by incorporating wind units. This can be achieved by minimizing the annual economic losses, which encompass the expenses associated with installation, operation, and maintenance, in addition to fluctuations in voltage and losses of power in the buses. The paper [4] discusses a novel multi-objective whale optimization algorithm (MOWOA) designed specifically for solving multi-objective problems. The study [5] focuses on enhancing the cost function or cost-effectiveness of electricity generation by strategically allocating wind, solar, and hydroelectric systems. The system assesses the degree of penetration (ranging from 0 to 100%) of various systems and develops generators that effectively transition to renewable resources.

The advanced search group algorithm (ESGA) [6] has been used for the purpose of optimizing the placement of DGs in distribution networks. The system utilizes radial networks (RDNs) to minimize power losses, enhance voltage stability, and improve voltage profiles. It effectively enhances network performance by employing appropriate power. Reference [7] presents a method that utilizes non-linear programming and the crow search algorithm to optimize the placement and sizing of hybrid SFCLs in distribution systems with synchronous DG. The objective is to minimize the size of the SFCLs and the operating time of the OCR, while also enhancing protection coordination with minimizing installation expenses. The paper [8] presents an optimal approach for positioning and assessing type IV induction generators in extensive wind farms. The objective is to effectively incorporate type IV induction generators and wind farms into unbalanced three-phase distribution networks. This study focuses on minimizing losses by utilizing Unified Power Quality Conditioner (UPQC) as a means of reactive power support, in conjunction with the Particle Swarm Optimization (PSO) algorithm. The outcomes of a two-step economic plan in [9] for incorporating synchronous DGs into conventional distribution networks validate the enhancement of protection coordination and economic metrics in comparison to power flow studies. Ref. [10] presents a method based on evolutionary optimization for determining the optimal location and reconfiguration of DGs in the standard IEEE 33-bus system. This method leads to considerable enhancements in voltage characteristics, reduction in power loss, and improved system reliability.

According to [11], an optimal approach is suggested for determining the quantity and placement of DGs in distribution networks, using nodal pricing as the basis. This study employs an enhanced artificial bee colony algorithm on a practical 38-bus system with voltage- and frequency-sensitive loads, with the objective of maximizing the profit of the distribution company. The researchers in [12] propose a highly effective approach to optimize the placement and capacity of DGs and transformers tap in distribution networks by analyzing and considering uncertainties. This is realized by minimizing the loss and improving the voltage stability using probabilistic nonlinear optimization. The study [13] employs three multi-objective algorithms to determine the optimal placement and quantity of DGs in power systems. The effectiveness of this approach is evaluated

using the standard IEEE 33-bus distribution network, and the results demonstrate a notable decrease in active power losses by strategically placing DGs, thereby enhancing system performance. In [14], a proposed approach suggests integrating electric vehicles (EVs) into unbalanced distribution systems using an optimal coordinated strategy. By employing Vehicle-to-Grid (V2G) technology and demand-side management for EVs, this method effectively finds resources that result in decreased power losses, enhanced voltage parameters, and lowered operating expenses. In their study, researchers in [15] suggest an optimal method for determining the location, generation level, and scheduling of energy storage sources with DGs in distribution networks. This methodology utilizes loss sensitivity factors and addresses uncertainties to prevent voltage deviation and minimize the voltage deviations and active power losses.

The objective of [16] is to reduce active and reactive power losses in power networks by implementing a genetic algorithm (GA) to maximize the capacity of DGs. Through simulation on standard IEEE 30- and 118-bus systems, this technique proves to be a promising strategy for sustainable energy systems. In [17], a novel approach is suggested to enhance voltage stability and reduce power losses in radial distribution networks. This approach involves the optimal positioning of DGs, network reconfiguration, and voltage control at buses using a gray wolf optimization algorithm for a multi-objective function. It enhances the voltage stability of the tested system to a notable extent. The researchers in [18] examine how the rated power and overall capacity of solar modules impact energy loss in radial distribution networks. They find that their multi-objective control strategy is more effective than alternative approaches in attaining reduced energy loss. The recommended power rating for each individual unit and the overall capacity for all units are provided to ensure the installation of an efficient solar system.

The strategy proposed in [19] aims to enhance voltage regulation in order to optimize distributed energy storage in imbalanced distribution networks. The researchers in this study utilize thorough voltage analysis to ascertain the most advantageous placement and dimensions of Distributed Energy Storage Systems (DESS) while simultaneously reducing costs with an enhanced gray wolf minimization technique. This approach effectively enhances voltage projects in unbalanced distribution networks, while also ensuring economic efficiency.

Based on the analysis of various articles and references, it has been observed that the strategic placement of generation sources in order to minimize losses, enhance voltage stability, and reduce network expenses has been achieved through methods such as optimization algorithms, solving non-linear equations, energy storage, and adjusting transformers tap. However, none of these approaches have addressed the issue of network self-healing, which will be the focus of this article.

This paper presents the architecture of a self-healing network that exhibits great dependability and minimal losses. To achieve this objective, the PSO algorithm will be employed to locate DG units throughout the network. Among the existing algorithms, this algorithm provides the most optimal solution, and the main reason for selecting this specific algorithm is its convergence speed, which presents the desired results in the least possible time. Identifying the most suitable locations for these sources will not only lead to a substantial reduction in losses but also enhance the voltage profile and the system's

reliability. Subsequently, the discussion will focus on the enhancement of network intelligence and self-healing capabilities. In this study, we examined the conventional 69-bus network and analyzed the simulation outcomes. Next, the second section will discuss the allocation of DGs to minimize losses, while the third section will outline the suggested self-repairing algorithm. This article is structured into five sections, with Section 1 serving as an introductory overview of the topic. Section 2 provides an explanation of the relationships associated with the placement of DGs to minimize losses, utilizing the PSO algorithm. Section 3 provides a comprehensive explanation of the theoretical framework behind the proposed self-healing algorithm. Section 4 outlines the outcomes of the software simulation test, while Section 5 provides the final conclusion.

2. Allocation of DGs to reduce losses

The PSO has been adopted here to find the proper size and location of DGs in a distribution system. The optimization problem is formulated as follows:

$$Min\ f\ (x)s.t.\ x_i \in X_i,\ i = 1,2,...,N \tag{1}$$

where $f(x)$ is the objective function, and x is the sum of each of the selected x_i variables. The value of X_i is the sum of the possible amplitude of each variable, and N is the number of variables.

2.1. Objective function

The optimization problem aims to determine the optimal size and precise placement of DGs to maximize the ratio of the benefits derived from employing these resources to their associated costs. Augmenting the quantity of DGs amplifies the advantages of this scheme, although it concurrently escalates the capital cost and substantially raises the overall cost. Consequently, as the number of DGs rises, so does the magnitude of their expenses. The objective function is defined by Equation (2):

$$\max f = \frac{Benefit}{Cost} \tag{2}$$

2.2. Advantages

- **Reduced power purchase**

The first advantage of using DGs is that with the generation of power by DG, the purchase of power from the main grid is reduced. Therefore, this reduction can be considered as an advantage in DGs in the form of Equation (3):

$$PS\ (\$/KWh) = \sum_{i=1}^{N_{DG}} P_{DG}^{i} \times \rho \tag{3}$$

Here, PS is the profit from the sale of power. N_{DG} is the number of installed DGs, P_{DG}^{i} is the amount of power produced by the ith DG, and ρ is the price of electricity. Considering the 5-year study period, inflation and interest rates should be considered in electricity cost calculations. The price of electricity per year can be calculated by Equation (4):

$$\rho^{i}\ (\$/KWh) = \rho^{0} \times \left(\frac{1+\ln fR}{1+\ln tR}\right)^{i-1} \tag{4}$$

Here ρ^0 is the cost of electricity in the first year, ρ^i is the cost of electricity in the ith year, and InfR and IntR denote the inflation and interest rates, respectively.

- **Loss reduction**

Another advantage of using DG is the reduction of losses due to energy generation in local loads and the elimination of transmission lines [20, 21]. Losses in the distribution system depend on the current and resistance of the transmission lines. Losses are a function of system topology and the size and location of DGs in the system. The loss reduction equation can be shown as Equation (5):

$$B_{Loss} = \left(Loss_{NDG} - Loss_{DG}\right) \times \rho \tag{5}$$

Here, $Loss_{NDG}$ and $Loss_{DG}$ show the losses without and with the use of DGs.

- **Reduced energy not-supplied (ENS)**

Reliability is another benefit that can be achieved using DGs and the ENS model. Fault location and fault clearance along the fault branch are used to calculate ENS [22, 23]. Sectionalizers and reclosers can reduce the range of fault impact and reduce the number of users experiencing long-term outages [23, 24]. The repair duration includes the time required to isolate the faulty branch, connect an emergency node, and repair the fault location. DGs that direct the power to the split branch can play a major role in improving reliability.

ENS costs can be calculated as in [25] according to Equation (6):

$$C_{ENS} = \sum_{i=1}^{N_{branch}} \sum_{j=1}^{N_t} \lambda_i L_i \rho_{\text{int}} t_i D_j \tag{6}$$

Here, C_{ENS} is equal to the cost of ENS per year, N_{branch} is the number of branches in the system, N_t is the number of loads interrupted due to fault in the ith branch, λ_i is the fault rate for each branch per kilometer per year, L_i is the length of the branch, t_i is the length of the repair period, ρ_{int} is the consumer price, and D_j denotes the load rate due to the fault in the ith branch.

The benefit of using DGs in reliability is as Equation (7):

$$\Delta C_{ENS} = C_{NDG}^{ENS} - C_{DG}^{ENS} \tag{7}$$

where C_{NDG}^{ENS} and C_{DG}^{ENS} are the ENS cost without DG and with DG. Also, the price of ENS should be calculated every year on the basis of bank interest and inflation and in the form of Equation (8):

$$\rho_i^{\text{int}} = \rho_0^{\text{int}} \times \left(\frac{1+\ln fR}{1+\ln tR}\right)^{i-1} \tag{8}$$

2.3. Costs

In this section, three types of costs are considered for DGs: initial, maintenance and performance, and investment costs [26].

- **Initial cost**

Initial costs include the costs related to the purchase, installation, and connection of DG units. The initial cost of DG is given in Equation (9) [26]:

$$IC_{DG}\left(\$/KWh\right)=\sum_{i=1}^{N_{DG}} C_i^{investment} \tag{9}$$

Here $C_i^{investment}$ is the cost necessary for purchasing and connecting the *i*th DG, and IC_{DG} is the total capital cost of all DGs.

- **Investment cost**

The investment cost includes the annual cost of fuel, taking into account the interest rate. In this case, the investment cost will be calculated in the form of Equation (10) [26]:

$$OC_{DG}\left(\$/KWh-year\right)=\sum_{i=1}^{N_{DG}} C_i^{operation} \tag{10}$$

The amount $C_i^{operation}$ is the investment cost of the *i*th DG and OC_{DG} is the investment cost for all DGs. This is an annual cost, and interest rates and inflation should be considered in them [26].

$$C_i^{operation}=C_0^{operation}\times\left(\frac{1+\ln fR}{1+\ln tR}\right)^{i-1} \tag{11}$$

- **Maintenance and operation cost**

The cost of maintenance and operation, which includes the costs related to the maintenance of DG units, is defined as Equation (12):

$$MC_{DG}\left(\$/KWh-year\right)=\sum_{i=1}^{N_{DG}} C_i^{maintenance} \tag{12}$$

where $C_i^{maintenance}$ is the maintenance and operation cost of the *i*th DG and MC_{DG} is the total cost for maintenance and operation of all DGs. This is an annual cost, and the amounts of interest and inflation should be considered in it. According to Equation (13), we have:

$$C_i^{maintenance}=C_0^{maintenance}\times\left(\frac{1+\ln fR}{1+\ln tR}\right)^{i-1} \tag{13}$$

2.4. Constraints

The constraints of the objective function include the following:

- **System voltage level**

$$V_{\min}\le V_i^{n}\le V_{\max}\quad n=1,2,\ldots,N \tag{14}$$

where V_i is the node voltage in year *i*, and *N* is the number of nodes of the system.

- **Short-circuit limits**

$$S_{\min}^{b}\le S_i^{b}\le S_{\max}^{b}\quad b=1,2,\ldots,B \tag{15}$$

where S_i^{b} is the apparent power at branch *b* in year *i*, and *B* represents the number of branches (transformers and lines).

- **Active and reactive power of the DG**

$$P_{DG\min}^{k} \le P_{DGi}^{k} \le P_{DG\max}^{k} \quad k = 1,2,\ldots,K \tag{16}$$

$$Q_{DG\min}^{k} \le Q_{DGi}^{k} \le Q_{DG\max}^{k} \quad k = 1,2,\ldots,K \tag{17}$$

where P_{DGi}^{k} and Q_{DGi}^{k} are the active and reactive power output of generator k in year i, and K is the number of DGs.

3. The proposed self-healing algorithm

This section provides a comprehensive description of the proposed self-healing algorithm for the network. The self-healing reconfiguration process is described here. When a fault occurs, the power recovery system detects the fault based on the data related to the distribution network in real time. Subsequently, it proposes an accurate and efficient reconfiguration technique to precisely identify the location of the fault, separate the faulty region, and promptly restore the unaffected regions. The challenge of self-healing reconfiguration in distribution networks can be characterized as a multi-objective, multi-period hybrid, multi-boundary nonlinear optimization problem, taking into account factors such as the number of switching operations, feeder load margin, load improvement amount, network restrictions, and user priority. Prior to elucidating the executed method, we provide an explanation of the objective functions, constraints, and the algorithm employed in the simulation [27].

3.1. Objective function

Different objective functions for the reconfiguration algorithm of self-healing distribution networks are presented according to different reconfiguration target conditions. The following two objectives are considered in this paper [27].

1) Objective functions with the least number of switching operations and minimum power loss

$$\min F(I,Y,Z) = \min\left\{ b_1 \left[\sum_{i=1}^{m} a_i (1 - y_i) + \sum_{j=1}^{n} a_{m+j} z_j \right] + b_2 \sum_{i=1}^{l} |I_i|^2 R_i \right\} \tag{18}$$

y_i and z_i show the status of disconnection and loop switches, m and n are the number of disconnection and loop switches, a_i is the weight coefficient, i denotes the number of branches, I_i represents the present amplitude of branch i, R_i is the resistance of branch i, b_1 is the cost coefficient of switch operations, and b_2 is the weight coefficient of active power loss.

2) To avoid overload and ensure the security and quality of the power supply, the objective function with uniform load becomes:

$$LB_i = \frac{S_i}{S_i^{\max}} \tag{19}$$

$$LB_{sys} = \frac{1}{n}\sum_{i=1}^{Nb}\frac{S_i}{S_i^{\max}} \quad (20)$$

where LB_i and LB_{sys} are the indices of load balance of branches and the system, S_i denotes the current flow on branch i, $S_i^{\max}$ is the capacity of the unit, and N_b represents the number of branches of the system. Due to the rapid increase in load and slow energy production, the load distribution of distribution networks is very uneven and has many disadvantages for the system, including increased energy consumption, reduced power quality, and overload risk. There are two main means of achieving load balancing. The first tool is to transfer the load between different feeders in the system and the other is to transfer the load between different phases in the feeder.

3.2. Constraints

The constraints of the self-healing reconfiguration algorithm of distribution networks include a set of equality constraints, including power flow constraints, and inequality constraints, including limits on feeder capacity, line current, bus voltage, and transformer overload [28].

a. Capacity limit of the feeder

$$S_j \le S_{j\max} \quad (21)$$

where S_j is the current power on route φ, and $S_{j\max}$ is the maximum power on that route.

b. Line current limit

$$I_{ij} \le I_{ij\max} \quad (22)$$

here, I_{ij} is the current flow on the route ij, and $I_{ij\,max}$ is the maximum current on that route.

c. Bus voltage limit

$$V_{j\min} \le V_j \le V_{j\max} \quad (23)$$

where $V_{j\max}$ and $V_{j\min}$ are the upper and lower limits of the node j voltage.

d. Transformer overload limit

$$S_t \le S_{t\max} \quad (24)$$

S_t is the transformer power, and $S_{t\,max}$ is the maximum power of the transformer.
In the self-healing reconfiguration process, inequality constraints are guaranteed by adding a penalty function to the objective functions.

3.3. Metaheuristic reconfiguration self-healing Algorithm

This part of the paper discusses the metaheuristic reconfiguration self-healing algorithm based on the tree structure.

- Metaheuristic rules

We divide the switches into the following three sets:
Set A: Switches that cannot be closed.
Set B: Switches that cannot be opened.

Set C: Switches that cannot be freely activated.
The following rules of thumb are provided with respect to the characteristics of distribution networks and self-healing reconfiguration requirements:
• Prioritizing operations to the switches connected to the transformer.
• Prioritizing the use of closed-loop switches to the power supply terminal. The situations where the load is connected to the distribution network affects the system loss, and the shorter the distance between the load and the power supply terminal, the less network loss.
• Prioritizing the operation of the lines with the maximum current margin.

3.4. Algorithm procedure

Step 1: First, search and find all the out-of-service areas, calculate the amount of load loss, and mark all the switches in this area.
Step 2: Count the number (defined as n) of loop switches that can be operational and do not belong to set A between the charging region and the out-of-service region. If $n = 0$, this means that there is no way to restore power and terminate the process.
Step 3: If $n \neq 0$ ‘, select a loop switch as the root node according to subjective rules; other nodes in the out-of-service area are formed into a tree according to the connection relationship. Then, according to the distance from the root node, put the numbers in the route of the buses and lines saved by the layer.
Step 4: Close the loop switch and return to Step 1 if the constraints are met.
Step 5: If the constraint is not satisfied, search the tree from the bottom up and open the switches of this layer until the constraint is satisfied, then return to Step 1. If the switches in this layer belong to sets B and C, open only the switches for set C. If the switches in this layer belong to set B, open all. Constraints are removed until the root node's loop switch is turned on, which means the loop switch cannot be closed, so mark it as set A. This algorithm process is also shown in Figure 1.

3.4.1. Self-healing reconfiguration of the distribution network with DGs

DGs generally adopt an active power or voltage control strategy when connected to the grid. When the agent is disconnected from the grid, the voltage/frequency control system is selected. According to different control strategies, DGs can be divided as follows: DGs that can run independently and DGs that cannot. Under the assumption of ensuring the safety of the power system, according to the different types of DGs, when a fault occurs in the distribution networks, the DGs that can operate independently form a controllable island, while the DGs that cannot operate independently are disconnected; the rest of the network is rebuilt using a self-healing reconfiguration method. Figure 2 shows this process.

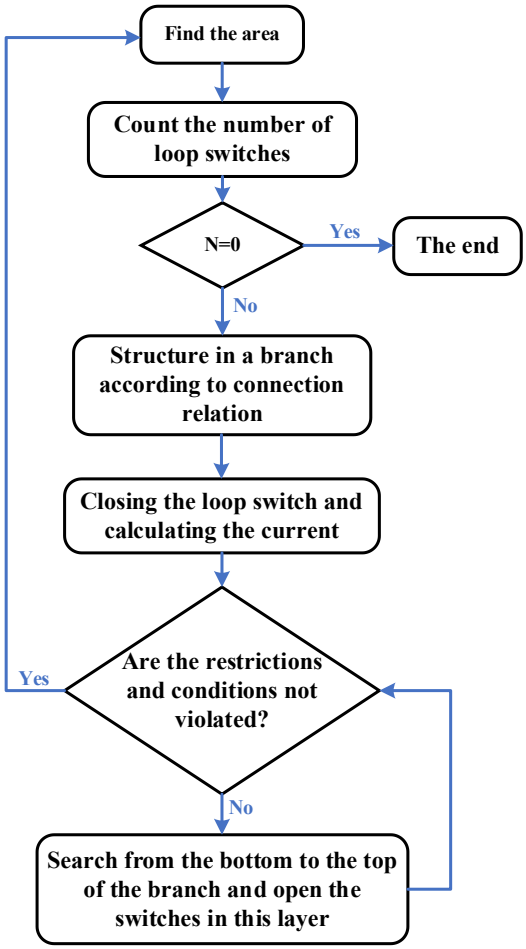

Figure 1. The flowchart of the metaheuristic reconfiguration self-healing algorithm.

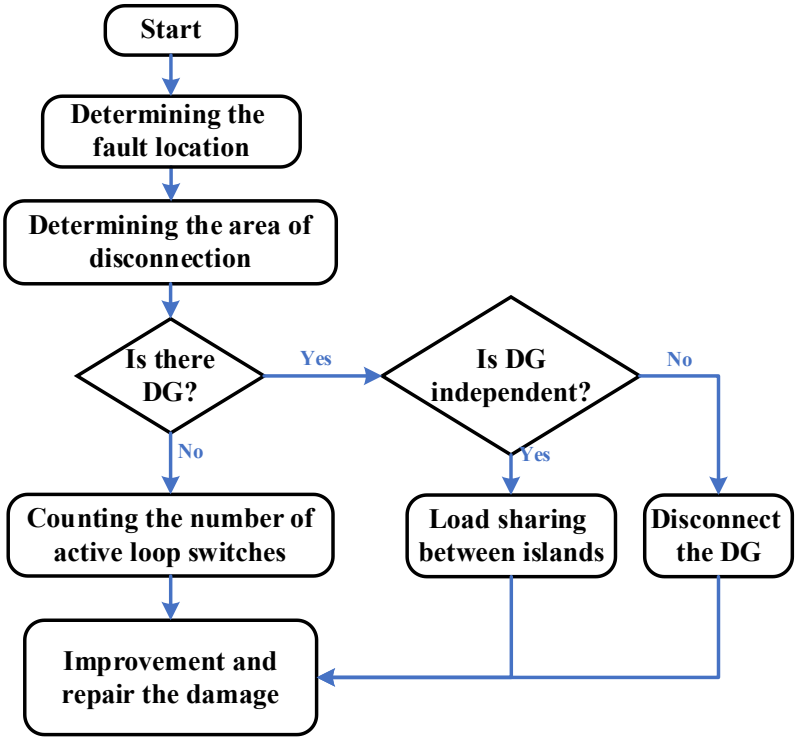

Figure 2. Self-healing reconfiguration of the distribution network with DGs.

An additional limitation of distribution networks with DGs is island power limitation, i.e., the load on an island must be less than the total supply from DG for this island.

$$P_{DG} + \sum_{\phi} P_i \geq 0 \tag{25}$$

where P_{DG} is the output power of the DG in the island, ϕ is the set of islands, and P_i is the loads within the island.

4. Simulation results

4.1. Allocation of DGs to reduce losses

The system under study is the standard IEEE 69-bus system, depicted in Figure 3. The power consumption of buses is 3.8 MW and 2.7 MVar in total, which are fed at a nominal voltage of 12.66 kV, in which case the network loss is equal to 224.98 kW.

Table 1 shows the location and size of energy sources and network losses after optimization. At the end of the optimization process, the global search reaches convergence around the optimal point during the 16th iteration. The utilization of DGs results in a consistent oscillation of the voltage profile around 1 per-unit (p.u.), as depicted in Figure 4. This phenomenon demonstrates a significant enhancement in voltage. Before the installation of DGs, the voltage profile in p.u. shows a significant reduction of 91% at the end of the lines.

To enhance the comparison in Figure 4, the voltage profile is juxtaposed prior to and subsequent to the implementation of energy sources. The addition of a 1.57 MW energy source at the end of the network resulted in a 10% improvement in the voltage profile at that location. Additionally, it should be noted that the storage devices are situated in the same location as the energy sources.

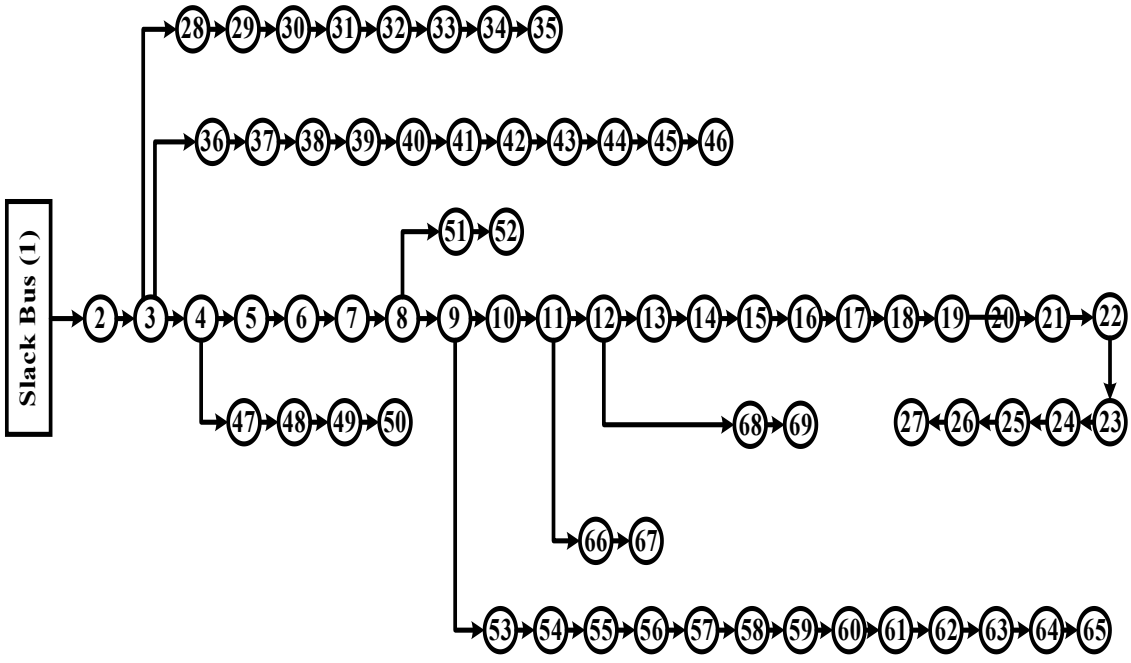

Figure 3. The standard IEEE 69-bus system under study [25].

Table 1. Location and optimal size of energy sources by the PSO method.

No.	Capacity	Location	No. of birds	Iteration s	Loss before installation of sources	Loss after installation of sources
DER 1	1.5766 MW	61	100	20	224.94kW	97.2kW
DER 2	0.46196 MW	17				

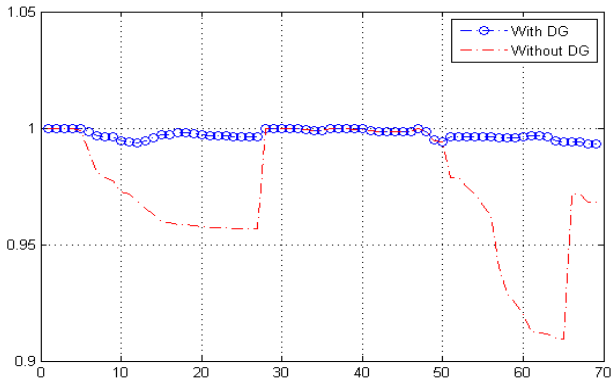

Figure 4. A comparison of voltage profiles before and after installation of DGS in the network.

4.2. Self-healing of the 69-bus distribution network

As previously mentioned, there are several DG protections switches in the vicinity. These switches are designed to open in the event of a fault during islanding. Additionally, there are a set of open switches that can be connected to create secondary and healing routes. In the event of a fault and disconnection of the faulty point, these switches help address any issues that may arise. Power quality, dependability, and stability in the network should not be compromised. While it is possible to define several intricate and diverse structures, the notable benefits of this technology include its rapid self-healing, reduced expenses, and overall simplicity.

Initially, the network is partitioned into 8 sections. Bus 1 to 3 comprise the primary route and do not have any associated load, so they are excluded from this segmentation. Partitioned areas are:

$$Area: [4-27; 28-35; 36-46; 47-50; 51-52; 53-65; 66-67; 68-69]$$

In this scenario, it is feasible to exclude less significant feeders with a low load in order to minimize the costs associated with switching and establishing an alternative route. Here, all feeders are provided with zoning to ensure that they can supply all network loads in case of fault occurrence. This zoning is also depicted in Figure 5. Then all areas are connected to each other through an open switch that can be connected at different points, which are alternative routes for the power of different feeders in case of fault. These switches are defined for different feeders as follows:

$$Disc\ Switches: [27-35; 35-46; 46-52; 27-50; 50-65; 65-68; 67-69]$$

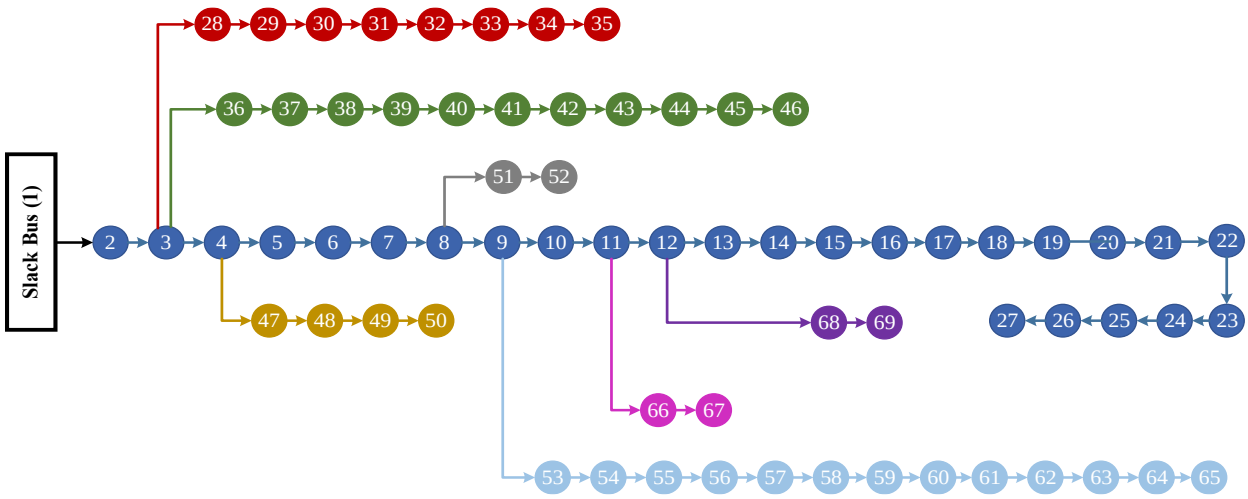

Figure 5. Network zoning.

These routes with connectable switches are also shown in Figure 6. The algorithm outlined below describes a method for finding self-healing. The first step involves identifying the specific area where the fault occurred and the affected consumer. Next, the algorithm checks the number of loop switches in the network. Starting from the fault location, it forms a loop by connecting the switch above the fault and establishes an alternative route. By opening the isolated switch, the data's status is altered, thereby isolating the DG source. This isolation allows for the delivery of load power by disconnecting the DG and connecting the upstream loop switches, enabling power flow. Self-healing is only possible if the voltage and power limits are upheld. In such cases, the self-healing is carried out using the same switch position. However, if the conditions are not met, the upstream switches are altered until the desired conditions are achieved. In order to evaluate the simulation's performance, we introduce a hypothetical fault in bus 28 and then in bus 26. We then calculate the switching cost and maintenance cost using Equation (18) and taking into account the self-healing characteristics of the network.

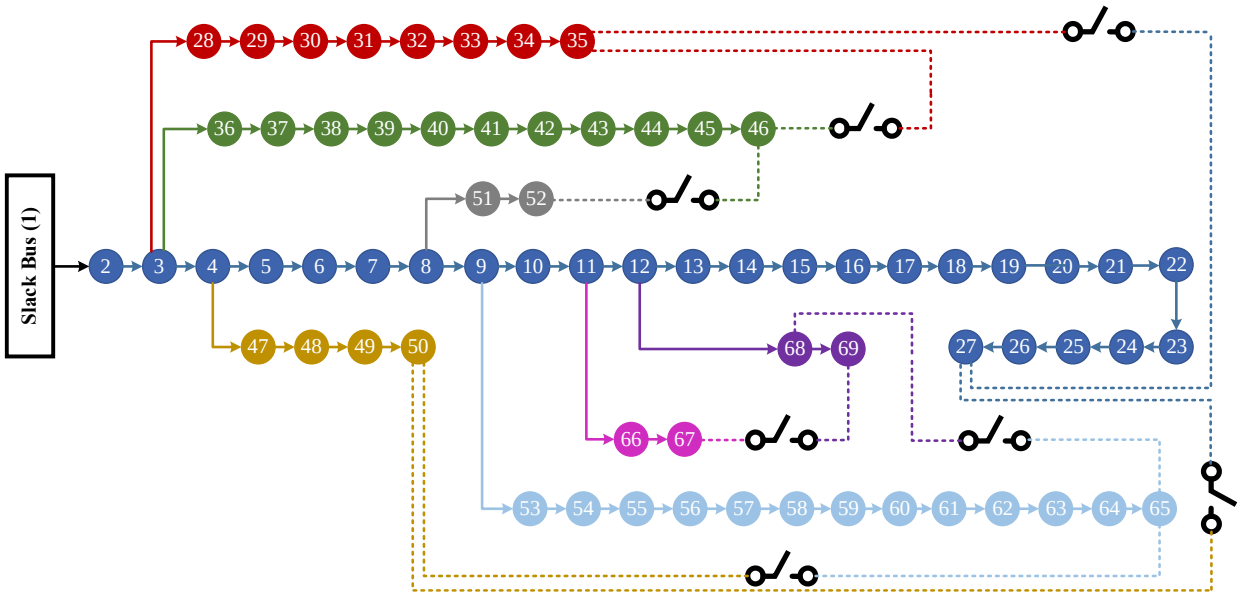

Figure 6. Secondary routes considered for the 69-bus network.

- A fault at bus 28

Given that bus 61 has a substantial load capacity of 1.3 MW, with 0.8 MW accounting for one-third of the overall network load, and the approximate capacity of bus 61 is 1.6 MW, the cost calculation formulation has concluded that in the event of islanding, DG should solely be accountable for supplying power to its own bus load, taking into consideration voltage constraints and the expenses associated with switching. Upon detecting a fault through the sensors and measurement devices, the self-healing network initiates the process of self-healing the network based on the prevailing conditions and the switching cost function. According to the information presented in Table 2, when a fault occurs at bus 28, the bus with DG becomes islanded and the route 65-68 as the first priority with the least total cost and the route 27-35 as the second priority with higher cost are established. The self-healing function is depicted in Figure 7.

- A fault at bus 26

The consideration of bus 26 was only due to the distance of the bus from the slack bus and it was random. An attempt was made to select one of the farthest buses from the slack bus. Considering that the desired method has been validated, the possibility of considering other points for fault is unimpeded. In this case, the self-healing approach is demonstrated in Table 3 and Figure 8, illustrating the performance of this function. When simulating self-healing, it is observed that the self-healing algorithm selects the route with the lowest cost after each fault. This is because, in other tested faults, routes 35-46 or 27-50 were found to have high costs and are not chosen unless low-cost routes are excluded or not taken into account.

Table 2. Self-healing strategy for a fault at bus 28.

Fault	No.	Switch status	Case	Cost
Bus 28	1	61-62 open 60-61 open	Islanded DG	65.7056
	2	65-68 closed 27-35 closed	Power source restoration	

Table 3. Self-healing strategy for a fault at bus 26.

Fault	No.	Switch status	Case	Cost
Bus 26	1	61-62 open 60-61 open	Islanded DG	103.2107
	2	46-52 closed 50-65 closed	Power source restoration	

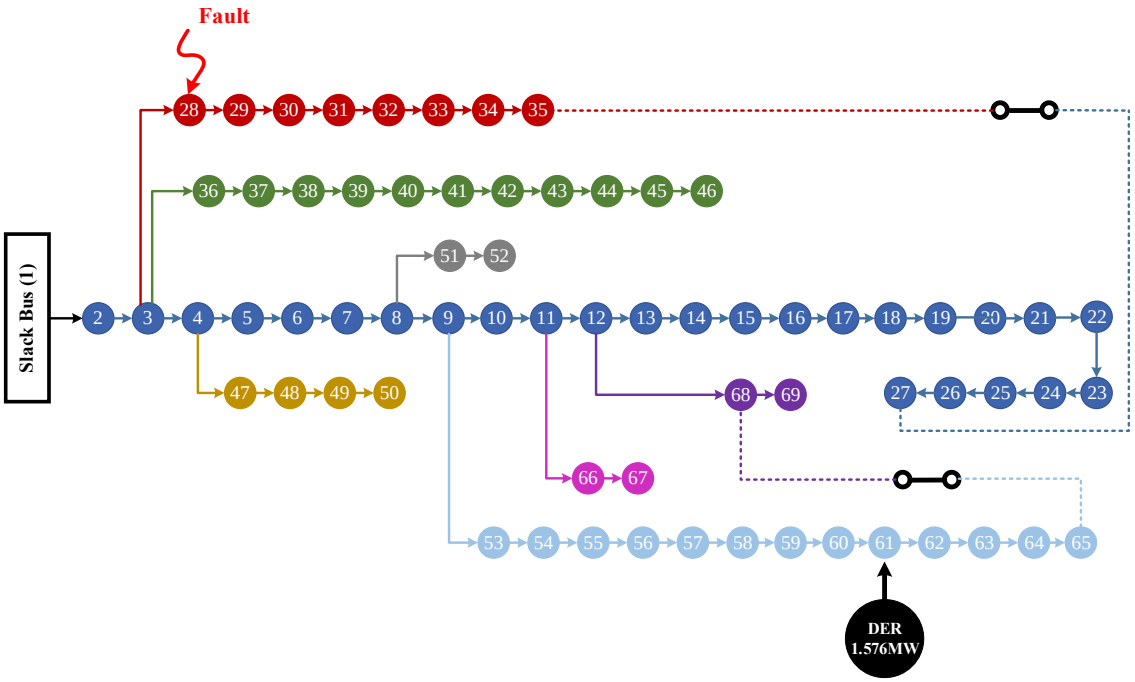

Figure 7. Self-healing performance in the case of a fault at bus 28.

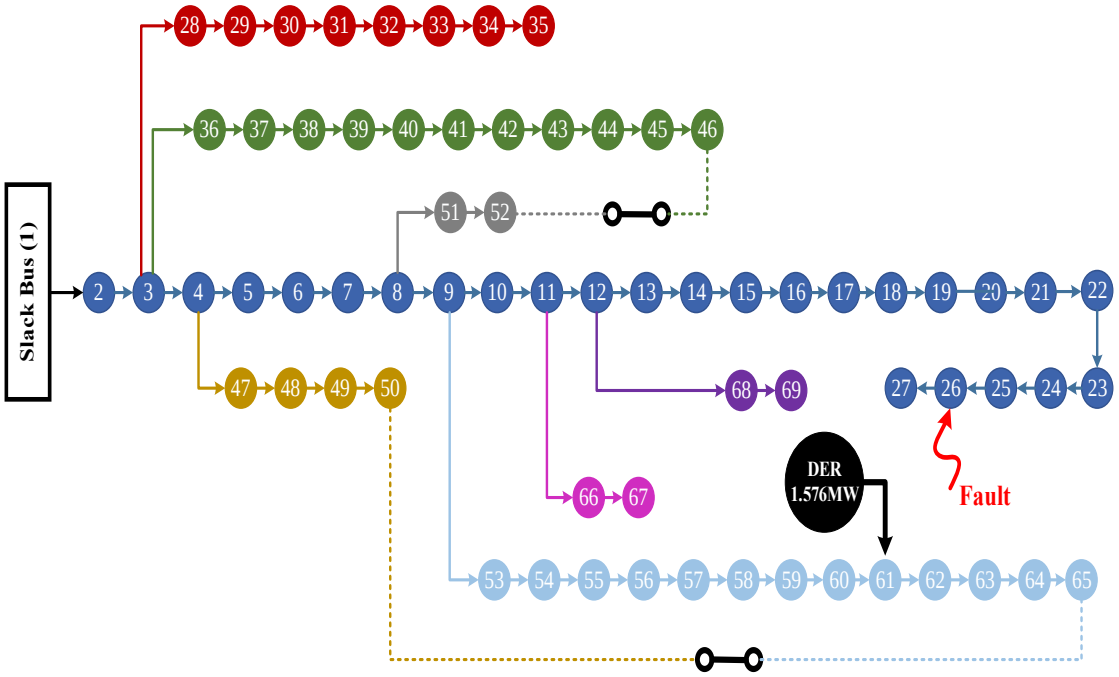

Figure 8. Self-healing performance in the case of a fault at bus 26.

5. Conclusions

This paper presents the design of a self-healing network with high reliability, minimal losses, and an improved voltage profile. The objective is to determine the best placement and capacity for DG units. In order to evaluate the effectiveness of the suggested approach, the algorithm was implemented on the standard IEEE 69-bus network. The simulation results of the self-healing process validated that, apart from selecting the route with the least cost, the algorithm substantially decreased the overall power loss and enhanced the

voltage profile. Moreover, through the implementation of intelligent devices, the network has been optimized, resulting in a highly efficient infrastructure. Additionally, the self-healing capabilities of this smart network have further enhanced its efficiency, minimizing human errors to an almost negligible extent. Consequently, the network's reliability has significantly improved, leaving a remarkable impression. In the end, it should be said that in future studies, the costs related to switches, including purchase, maintenance, and costs related to switching, can be considered in locating distributed generation resources. Also, the hidden costs of distributed generation resources, including the efficiency and switching of power electronic circuits and life span, are items that can be effective in locating the distributed generation resources. As a verification, the location of the fault, the type of fault, and the number of distributed generation sources added to the network can be considered as variables for the next location studies.

References

[1] M. Falah Nezhadnaeini, M. Hajivand, M. Abasi, and S. Mohajerami, "Optimal Allocation of Distributed Generation Units Based on Different Objectives by a Novel Version Group Search Optimizer Algorithm in Unbalance Load System," *Rev Roumaine des Sciences Techniques-Series Electrotechnique et Energetique*, vol. 61, no. 4, pp. 338–342, 2016.

[2] S. M. R. H. Shawon, X. Liang, and M. Janbakhsh, "Optimal Placement of Distributed Generation Units for Microgrid Planning in Distribution Networks," *IEEE Transactions on Industry Applications*, vol. 59, no. 3, pp. 2785-2795, 2023.

[3] M. Abasi, M. Falah Nezhadnaeini, M. Karimi, and N. Yousefi, "A Novel Metaheuristic Approach to Solve Unit Commitment Problem in the Presence of Wind Farms," *Rev Roumaine des Sciences Techniques-Series Electrotechnique et Energetique*, vol. 60, no. 3, pp. 253–262, 2015.

[4] K. Subbaramaiah and P. Sujatha, "Optimal DG Unit Placement in Distribution Networks by Multi-Objective Whale Optimization Algorithm & Its Techno-Economic Analysis," *Electric Power Systems Research*, vol. 214, 108869, 2023.

[5] I. P. Idoko, T. R. Ayodele, et al., "Maximizing the Cost Effectiveness of Electric Power Generation Through the Integration of Distributed Generators: Wind, Hydro and Solar Power," *Bulletin of the National Research Centre*, vol. 47, 166, 2023.

[6] T. H. B. Huy, D. N. Vo, K. H. Truong, and T. Van Tran, "Optimal Distributed Generation Placement in Radial Distribution Networks Using Enhanced Search Group Algorithm," *IEEE Access*, vol. 11, pp. 103288-103305, 2023,

[7] M. Sadeghi, and M. Abasi, "Optimal Placement and Sizing of Hybrid Superconducting Fault Current Limiter to Protection Coordination Restoration of the Distribution Networks in the Presence of Simultaneous Distributed Generation," *Electric Power Systems Research*, vol. 201, 107541, 2021.

[8] M. Pushkarna, H. Ashfaq, et al., "An Optimal Placement and Sizing of Type-IV DG With Reactive Power Support Using UPQC in an Unbalanced Distribution System Using Particle Swarm Optimization," *Energy System,* vol. 15, pp.353-370, 2022.

[9] S.M. Sadeghi, M. Daryalal, and M. Abasi, "Two-stage Planning of Synchronous Distributed Generations in Distribution Network Considering Protection Coordination Index and Optimal Operation Situation," *IET Renewable Power Generation*, vol. 16, no. 11, pp. 2338-2356, 2022.

[10] M. A. Shaik, P. L. Mareddy, and N. Visali, "Enhancement of Voltage Profile in the Distribution system by Reconfiguring with DG placement using Equilibrium Optimizer," *Alexandria Engineering Journal*, vol. 61, no. 5, pp. 4081-4093, 2022.

[11] M. Dashtdar, M. Najafi, et al., "Placement and Optimal Size of DG in the Distribution Network Based on Nodal Pricing Reduction with Nonlinear Load Model Using the IABC Algorithm," *Sadhana*, vol. 47, 73, 2022.

[12] S. Das, O. B. Fosso, and G. Marafioti, "Probabilistic Planning of Distribution Networks with Optimal DG Placement Under Uncertainties," *IEEE Transactions on Industry Applications*, vol. 59, no. 3, pp. 2731-2741, 2023.

[13] B. N. Alajmi, M. F. AlHajri, et al., "Multi-objective Optimization of Optimal Placement and Sizing of Distributed Generators in Distribution Networks," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 18, no. 6, pp. 817-833, 2023.

[14] S. Mondal, and M. De, "Optimal Allocation and Smart Scheduling of Distributed Energy Resources and Electrical Vehicles to Enhance Economical Operation of Unbalanced Distribution System," *Electrical Engineering*, vol. 105, pp. 3493–3510, 2023.

[15] A. Ahlawat, and D. Das, "Optimal Sizing and Scheduling of Battery Energy Storage System with Solar and Wind DG Under Seasonal Load Variations Considering Uncertainties," *Journal of Energy Storage*, vol. 74, 109377, 2023.

[16] S. Mirsaeidi, S. Li, et al., "A Power Loss Minimization Strategy Based on Optimal Placement and Sizing of Distributed Energy Resources," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 35, no. 4, 2022.

[17] A. K. Barnwal, L. K. Yadav, and M. K. Verma, "A Multi-Objective Approach for Voltage Stability Enhancement and Loss Reduction Under PQV and P Buses Through Reconfiguration and Distributed Generation Allocation," *IEEE Access*, vol. 10, pp. 16609-16623, 2022.

[18] L. C. Kien, T. T. Nguyen, et al., "A Study on the Placement of Photovoltaic Units in the North and South of Vietnam for Energy Loss Reduction by Using a Proposed Slime Mould Algorithm," *Neural Computing and Applications*, vol. 35, pp. 23225–23247, 2023.

[19] Y. Li, and H. Cai, "Improving Voltage Profile of Unbalanced Low-Voltage Distribution Networks via Optimal Placement of Single-Phase Distributed Generation and Shunt Capacitors," *International Journal of Electrical Power & Energy Systems*, vol. 137, 107799, 2022.

[20] M. Abasi, M. Joorabian, A. Saffarian, and S. G. Seifossadat, "A Comprehensive Review of Various Fault Location Methods for Transmission Lines Compensated by FACTS Devices and Series Capacitors," *Journal of Operation and Automation in Power Engineering*, vol. 9, no. 3, pp. 213-225, 2021.

[21] M. Abasi, A. Saffarian, M. Joorabian, and S. G. Seifossadat, "Location of Double-Circuit Grounded Cross-Country Faults in GUPFC-Compensated Transmission Lines Based on Current and Voltage Phasors Analysis," *Electric Power Systems Research*, vol. 195, 107124, 2021.

[22] M. Abasi, A. Torabi Farsani, A. Rohani, and M. Aghazadeh Shiran, "Improving Differential Relay Performance During Cross-Country Fault Using a Fuzzy Logic-based Control Algorithm," *5th Conference. on Knowledge-Based Engineering and Innovation (KBEI)*, Iran, 2019.

[23] M. Abasi, A. Torabi Farsani, A. Rohani, and A. Beigzadeh, "A Novel Fuzzy Theory-Based Differential Protection Scheme for Transmission Lines," *International Journal of Integrated Engineering*, vol. 12, no. 8, pp. 149-160, 2020.

[24] M. Abasi, N. Heydarzadeh, and A. Rohani, "Broken Conductor Fault Location in Power Transmission Lines Using GMDH Function and Single-Terminal Data Independent of Line Parameters," *Journal of Applied Research in Electrical Engineering*, vol. 1, no. 1, pp. 22-32, 2021.

[25] B. Liu, Z. Yuan, and H. Bao, "Intelligent Optimization Algorithm for the Locating and Sizing of Distributed Generation Planning," *China International Conference on Electricity Distribution (CICED)*, pp.1-6, 2010.

[26] M. H. Moradi and M. Abedini, "A Combination of Genetic Algorithm and Particle Swarm Optimization for Optimal DG Location and Sizing in Distribution Systems," *International Journal of Electrical Power & Energy Systems*, vol. 34, no. 1, pp. 66-74, 2012.

[27] D. Li, S. Wang, J. Zhan, and Y. Zhao, "A Self-Healing Reconfiguration Technique for Smart Distribution Networks with DGs," *International Conference on Electrical and Control Engineering (ICECE)*, pp. 4318-4321, 2011.

[28] J. Moshtagh, and S. Ghasemi, "Optimal Distribution System Reconfiguration Using Nondominated Sorting Genetic Algorithm (NSGA-II)," *Journal of Operation and Automation in Power Engineering*, vol. 1, no. 1, pp. 12-21, 2013.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Ali Kazemi: Conceptualization, Formal analysis, Investigation, Methodology, Roles/Writing - original draft, Writing - review & editing. **Ali Morsagh Dezfuli:** Conceptualization, Resources, Methodology, Roles/Writing - original draft, Writing - review & editing.

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